A Study of $e^+e^- \to H^0A^0$ Production and the Constraint on Dark Matter Density

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This paper reports the results of a study of the $e^+e^- \to H^0A^0$ process at $\sqrt{s} = 1$ TeV performed on fully simulated and reconstructed events. The estimated accuracies on the heavy Higgs boson masses, widths and decay branching fractions are discussed in relation to the study of Supersymmetric Dark Matter.

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I. INTRODUCTION

The connections between cosmology and particle physics through dark datter (DM) have recently received special attention for defining the physics program at the TeV frontier. We foresee that the combination of data from satellites, direct DM searches, hadron and lepton colliders will provide a major breakthrough in our understanding of the nature of dark matter and its interactions in the early Universe. These expectations are supported by the fact that there are several extensions of the Standard Model (SM), which include a new, stable, weakly-interacting massive particle, which may be responsible for the observed relic DM in the Universe. This particle should become accessible to particle colliders operating at the TeV energy frontier, as well as to the next generations of direct DM search experiments. The LHC collider will be first in providing data to address the question of whether one of these scenarios is indeed realised in nature. If this is the case, it will also gather some quantitative information to be related to the relic DM density measured from the cosmic microwave background (CMB) spectra [1]. However, it is understood that the LHC data will not be exhaustive in this respect. First, it will not be possible to infer, in a model independent way, the relic density to an accuracy close to that already achieved by CMB observations. Furthermore, there exist classes of models of new physics which the LHC may not be able to disentangle and probe in sufficient details. It is only with the measurements becoming available at an electron positron collider, operating at centre-of-mass energies of order of 1 TeV, that we shall be able to determine the properties of the DM candidate particle and of the other particles participating in its interactions in the early Universe, with sufficient accuracy to predict the DM relic density precisely. With these results in hand, the comparison of the data from CMB experiments, direct DM searches and collider experiments would have striking consequences on our quantitative understanding of the nature and distribution of dark matter in the Universe.

In these years preceding LHC operation, Supersymmetry has emerged as the best motivated theory of new physics beyond the SM. It solves a number of open problems intrinsic to the SM and, most important to our discussion, the conservation of R-parity introduces the lightest neutralino, χ_1^0, as a new stable, weakly interacting particle. CMB data from the WMAP satellite, and other astrophysical data, already set rather stringent bounds on the parameters of Supersymmetry, if the lightest neutralino is responsible for saturating the amount of DM observed in the Universe. The recently released, five-year WMAP data provide a determination of the dark matter density as $\Omega_{\mathrm{CDM}}h^2 = 0.110 \pm 0.006$ [2].

The potential of the LHC and of an e^+e^- linear collider operating at 0.5 TeV and 1.0 TeV, such as the International Linear Collider (ILC), for determining the neutralino relic density, Ω_χ, in Supersymmetry has been investigated in detail in [3]. That study selected a set of benchmark points, the so-called LCC points, representative of various Supersymmetric scenarios and determined the Ω_χ probability density function by a scan of the full parameter space of the Minimal Supersymmetric extension of the SM (MSSM), by retaining those points compatible with the measurements available at the LHC and ILC, within their experimental accuracy.

In this paper we consider one of the Supersymmetric scenarios defined in [3], for which the neutralino relic density is controlled by its annihilation rate through the CP-even heavy Higgs pole $\chi\chi \to A^0$, which in turn crucially depends on the value of the mass of the boson, M_{A^0}. We study the accuracy of the measurement of the relevant properties of the neutral heavy Higgs boson A^0: its mass, M_{A^0}, width, Γ_{A^0} and decay branching fractions as can be obtained from data collected in high luminosity e^+e^- collisions at centre-of-mass energy of 1 TeV, using full simulation of the response of a realistic detector model and detailed event reconstruction.

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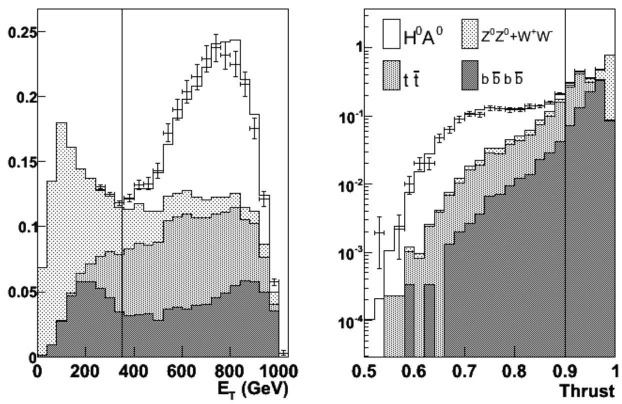

FIG. 1: Tranverse energy and thrust distributions for signal and background. Generator level distributions are plotted as histograms, results of `Mokka + Marlin` simulation and reconstruction are given for the signal process as points with error bars. All histograms are normalized to unit area.

II. $e^+e^- \rightarrow H^0A^0$ AT LCC-4 WITH FULL SIMULATION

We adopt the LCC-4 benchmark point of [3], which is defined in the reduced paramater space of the constrained MSSM by m_0=380 GeV, $m_{1/2}$=420 GeV, $\tan\beta$=53, A=0, $Sgn(\mu)$=+1 and M_{top}=178 GeV. We use `Isasugra 7.69` [4] to compute the physical particle spectrum and we get M_{A^0}=419.4 GeV, $M_{\chi_1^0}$=169.1 GeV and $M_{\tilde{\tau}_1}$=195.5 GeV. These parameters correspond to a neutralino relic density of $\Omega_\chi h^2 = 0.108$, as obtained by using the `microMEGAS 2.0` program [5]. The $e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$ process at $\sqrt{s}$ = 1 TeV has already been studied for LCC-4 using a parametric simulation [6]. We now perform a detailed study using `Geant-4`-based full simulation [7] of the detector response and reconstruct the physics objects using processors developed in the `Marlin` framework [8] and extend the analysis to both the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ final states. This study adopts the LDC detector concept, which is based on a large continuous gaseous tracker, a Time Projection Chamber, surrounded by a highly granular SiW calorimeter and complemented by a high resolution Si Vertex Tracker. The LDC detector concept is discussed in detail elsewhere[9], the design is optimised for achieving excellent parton energy measurements through the particle flow algorithm, and precise extrapolation of particle tracks to their production point. Both of these features are important to this analysis, which aims at suppressing backgrounds by exploiting the signature 4-b and 2-b + 2-τ final states of the signal, and requires good determinaton of energy and direction of hadronic jets to attain an optimal resolution on di-jet invariant mass.

Signal events have been generated with `Pythia 6.205` [17] + `Isasugra 7.69`, including beamstrahlung effects [18]. At $\sqrt{s}$ = 1 TeV, the effective $e^+e^- \rightarrow H^0A^0$ production cross section, accounting for beamstrahlung and initial state radiation, is 1.4 fb, BR($A^0 \rightarrow b\bar{b}$) = BR($H^0 \rightarrow b\bar{b}$) = 0.87 and BR($A^0 \rightarrow \tau^+\tau^-$) = BR($H^0 \rightarrow \tau^+\tau^-$) = 0.13. The main particle pair production backgrounds, Z^0Z^0, W^+W^- and $t\bar{t}$, have been generated using `Pythia`. Their cross sections, computed using `CompHep 4.4.0` [19], are 0.17 pb, 3.0 pb and 0.19 pb respectively. The inclusive $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ production, after subtracting the contribution of the Z^0Z^0 channel and requiring 200 GeV < M_{bb} < 600 GeV, have cross sections of 0.63 fb and 0.28 fb respectively. These processes have been generated at parton level using `CompHep` and then hadronised with `Pythia`. We assume to operate the linear collider at $\sqrt{s}$=1 TeV for a total integrated luminosity of 2 ab^{-1}, which corresponds to 5 years (1 yr = 10^7 s) of operation for a nominal luminosity of 4×10^{34} cm^{-2} s^{-1}.

A loose event preselection based on event variables has been applied after generation. Selected signal and background events have been passed through the full LDC simulation using the `Mokka 06-03` program [10], an ILC-specific implementation of `Geant-4`. Data are persisted using `lcio` [11] collections and used as input for the subsequent reconstruction in `Marlin`.

Pattern recognition and track fit are performed first using Monte Carlo truth information ("MC truth patrec") and, for signal events, also genuine full pattern recognition ("full patrec"), using the `FullLDCTracking` package based on DELPHI experiment software [12]. The performances of these two approaches are compared. The `Pandora v02-00` package is used for particle flow [13]. Jet clustering is performed using the DURHAM algorithm [14]. The jet energy resolution has been studied using a simulated sample of single b jets in the energy range from 10 GeV to 210 GeV over a polar angle, $0.4 < \theta < \pi/2$. We get $\delta E/E = (0.34 \pm 0.02)/\sqrt{E} \oplus (0.015 \pm 0.005)$, which is consistent with the LDC particle flow performance specifications. Jet flavour tagging is performed using the `LCFIVertex` package, which developed the original `ZVTOP` tagger [15] and feeds track and vertex topological information into a neural network to distinguish between b, c and light quark jets. The di-jet mass resolution in the $b\bar{b}b\bar{b}$ has been improved by performing a constrained kinematic fit. We have ported the `PUFITC` algorithm [16], developed for the DELPHI experiment at LEP2, into a dedicated `Marlin` processor. The algorithm adjusts the momenta of the jets given by $\vec{p}_F = e^a\vec{p}_M + b\vec{p}_B + c\vec{p}_C$ where $\vec{p}_F$ is the fitted momentum, $\vec{p}_M$ is the measured momentum, $\vec{p}_B$ and $\vec{p}_C$ are unit vectors transverse to $\vec{p}_M$ and to each other, and a, b and c are free parameters in the fit. The adjusted momenta satisfy a set of constraints while minimising the fit χ^2, given by $\Sigma_i\ (a_i - a_0)^2/\sigma_a^2 + b_i^2/\sigma_b^2 + c_i^2/\sigma_c^2$, where a_0 is the expected energy loss parameter, σ_a is the energy spread parameter and σ_b, σ_c are the transverse momentum spread parameters. In this analysis, we impose the following constraints: $p_x = p_y = 0$ and $E \pm |p_z| = \sqrt{s}$, where the last condition accounts for beamstrahlung along the

beam axis, z.

A. The $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$ Channel

First we analyse the fully hadronic final state. This provides with characteristics four b jet, symmetric events. The backgrounds can be significantly suppressed using b-tagging, event-shape and kinematic variables. We require selected events to fulfill the following criteria: total recorded energy in the event $E_{\rm tot} > 700$ GeV, total transverse energy E_T >350 GeV, total number of reconstructed particles $N_{\rm tot}$ >80, number of charged particles $N_{\rm cha}$ >30, event thrust <0.9 and Y_{34} >0.002, where Y_{34} is the 3 to 4 jet cross-over value of the jet clustering algorithm. The distributions of some of these variables are shown in Figure 1 for backgrounds and signal, for which a comparison of the generator-level and reconstructed values is also given. After event selection, particles are forced into four jets, which are arranged into two di-jet pairs, using the pairing which minimises the difference between the di-jet masses, M_{jj}. The kinematic fit is performed and a cut applied on the resulting di-jet mass difference $|M_{jj1} - M_{jj2}|$ <50 GeV to eliminate poorly reconstructed events. Both di-jet masses are required to satisfy M_{jj} >200 GeV. The event is required to have four b jets, where a b jet is determined by the following criteria: total jet multiplicity $N_{\rm tot}$ >10, charged jet multiplicity N_{cha} >5, and b jet probability, P_b, larger than 0.5. At the chosen working point, an efficiency for b jets of 0.79 is obtained, using "MC truth patrec", with sufficient rejection of lighter quarks to effectively suppress the remaining non-b backgrounds. By using "full patrec" without retraining the neural net, we measure a tagging efficiency of 0.72 per jet.

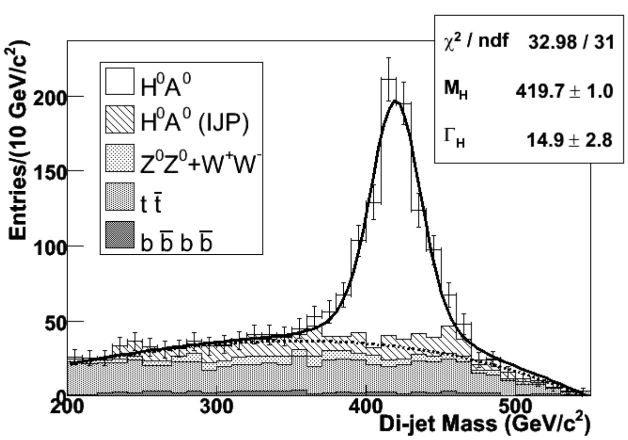

FIG. 2: Di-jet invariant mass distribution for signal and background events selected by the analysis cuts. Kinematic fit and jet flavour tagging have been applied. H^0A^0 events, in which the incorrect jet pairing (IJP) is chosen, are considered as background.

The di-jet mass for signal H^0A^0 events fulfilling the selection cuts has a Gaussian resolution of 23 GeV using tracks reconstructed with "MC truth patrec" and 27 GeV using tracks from "full patrec" before the kinematic fit. After applying the kinematic fit the di-jet mass resolutions become 13.7 GeV and 13.8 GeV, respectively

After final selection, the sample of events with di-jet masses in the region 200 GeV $< M_{jj} <$ 550 GeV gives a selection efficiency for signal $b\bar{b}b\bar{b}$ decays of 0.24±0.01 using tracks reconstructed with "MC truth patrec" and 0.17±0.01 using "full patrec". The difference is mostly caused by the observed drop in b-tagging efficiency. The corresponding acceptance for Z^0Z^0, W^+W^-, $t\bar{t}$ and inclusive $b\bar{b}b\bar{b}$ background events is 7×10^{-5}, 7×10^{-6}, 8×10^{-4} and 4×10^{-3}, respectively. The resulting mass distribution is shown in Figure 2, which has two entries per event. The signal is described by the convolution of two Breit-Wigner functions with a mass splitting of 1.4 GeV, as predicted for the LCC-4 parameters, convoluted with a double Gaussian resolution function. The background is described by a third-order polynomial with coefficients determined on background only events. The final fit function consists of a linear combination of the signal and background functions with four free parameters: M_A, Γ_A, and the weights of the signal and background functions. We get $M_A = (419.7\pm1.0)$ GeV and $\Gamma_A = (14.9\pm2.9)$ GeV, where the quoted uncertainties are statistical only. This result is remarkably close to that obtained in the earlier analysis, based on parametric detector simulation. Using "full patrec" the uncertainties on the A^0 boson mass and width increase to 1.3 GeV and 3.4 GeV, respectively.

B. The $e^+e^- \to H^0A^0 \to b\bar{b}\tau^+\tau^-$ Channel

The mixed decay mode $b\bar{b}\tau^+\tau^-$ can be isolated by tagging a $b\bar{b}$ di-jet, consistent with originating from either a H^0 or a A^0 decay and analysing the remaining particles in the event. We require the events to fullfill the following criteria: E_{tot} >400 GeV, 200 GeV< E_T <900 GeV, 40< N_{tot} <180, 15< N_{cha} <100, event thrust<0.8, event sphericity >0.1 and Y_{34} >0.005. The event is forced to four jets of which two must be tagged as b jets using the same criteria as above but the tighter requirement $P_b > 0.9$. The invariant mass of the bb di-jet must satisfy 300 GeV< M_{bb} <600 GeV, and that of the two remaining jets 250 GeV< M_{jj} <600 GeV. The angle between the two b jets and the angle between the two un-tagged jets must satisfy -0.8< $\cos\theta$ <0. The number of charged particles with energy greater than 5 GeV which are not associated to either of the b jets must not exceed six. Finally, τ tagging is performed. We have developed an algorithm which outputs a linear discriminant variable P_τ based on the jet mass, the impact parameter of the leading track, and a variable, P_{ISOL}, which measures the jet energy deposited in an annulus around the jet direction. At least one of the two non-b jets must be tagged as a τ jet, where a τ jet must have less than four energetic charged par-

ticles and must satisfy $P_\tau >0.8$. To distinguish between signal $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ decays, a discriminant variable P_{DISC} is calculated based on the un-tagged dijet energy, the number of energetic charged particles not associated to either of the two b jets, and P_τ^{MAX}, the larger of the two tau jet probabilities (see Figure 3). The event must satisfy $P_{DISC} >0.9$. After applying these cuts, the efficiency for signal $b\bar{b}\tau^+\tau^-$ decays is 0.14±0.02, that for the $t\bar{t}$ background is 2×10^{-4}, for Z^0Z^0 and W^+W^- is 3×10^{-8} while for $b\bar{b}b\bar{b}$ events is 2×10^{-6}. The selection criteria yield 87 events of signal with 89 of background, corresponding to a relative statistical uncertainty of 0.15 on the determination of BR(H^0, $A^0 \to \tau^+\tau^-$).

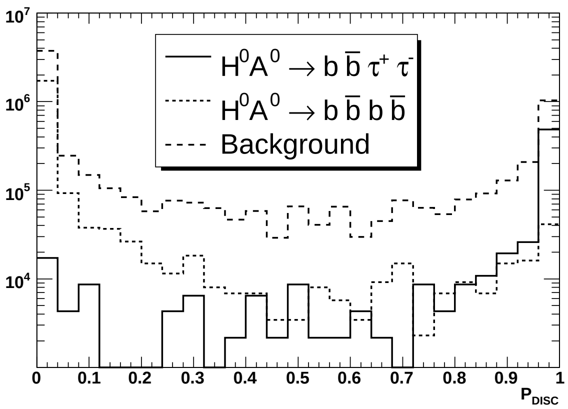

FIG. 3: Distribution of the discriminating variable adopted for separating $b\bar{b}\tau^+\tau^-$ events.

III. FURTHER CONSTRAINTS ON Ω_χ

The constraints on LCC-4 derived from this determination of the A^0 mass and width and other supersymmetric particle mass measurements at the LHC and a 1 TeV linear collider, provide a prediction of the neutralino relic density with a relative accuracy of 0.18, within the general MSSM [3]. The main contribution to the remaining uncertainty comes from the weak constraint which data provide to MSSM solutions where Ω_χ is significantly lower than its reference value for LCC-4. A detailed study shows that these solutions are all characterised by large values of the stau trilinear coupling, A_τ. In the MSSM the $\tilde{\tau}$ coupling to the H^0 and A^0 bosons scales as $A_\tau \frac{\cos\alpha}{\cos\beta} + \mu \frac{\sin\alpha}{\cos\beta}$ and $A_\tau \tan\beta + \mu$, respectively. It has been proposed to determine A_τ through a measurement of the branching fraction of A^0, $H^0 \to \tilde{\tau}_1\tilde{\tau}_2$ [20]. In the funnel region the main neutralino annihilation mechanism is $\tilde{\chi}^0\tilde{\chi}^0 \to A^0 \to b\bar{b}$ and $M_A < M_{\tilde{\tau}_1} + M_{\tilde{\tau}_2}$. The only A^0 decay into $\tilde{\tau}$s allowed by CP symmetry is $A^0 \to \tilde{\tau}_1\tilde{\tau}_2$ which is kinematically forbidden for the LCC-4 parameters. However, at large values of $|A_\tau|$, the $H^0 \to \tilde{\tau}_1\tilde{\tau}_1$ decay gets a sizeable enhancement of its branching fraction.

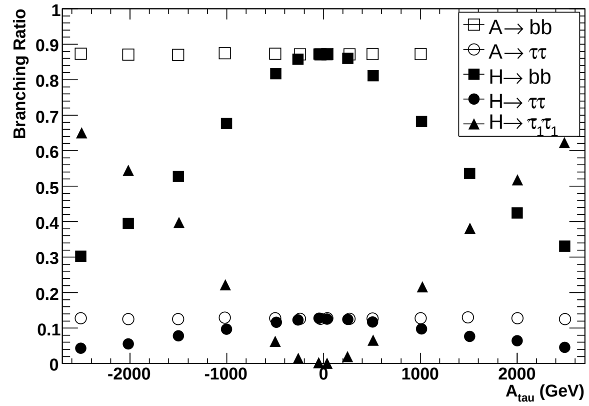

FIG. 4: H^0 and A^0 decay branching fractions as a function of the stau trilinear coupling A_τ as predicted by `HDECAY`. All the other MSSM parameters have been kept fixed to those of the LCC-4 point.

In this regime, this channel also contributes to the neutralino annihilation rate through the $\tilde{\chi}^0\tilde{\chi}^0 \to H^0 \to \tilde{\tau}_1\tilde{\tau}_1$ process, thus lowering the corresponding relic density, as observed in the MSSM scans. At the same time, a determination of the branching fraction of the decay $H^0 \to \tilde{\tau}_1\tilde{\tau}_1$, allows us to constrain the stau trilinear coupling. Figure 4 shows the decay branching fractions of the A^0 and H^0 bosons computed using the `HDECAY 2.0` program [21] as a function of the A_τ parameter. Now, due to the same final state, a large $H^0 \to \tilde{\tau}_1\tilde{\tau}_1 \to \tau\tilde{\chi}^0\tau\tilde{\chi}^0$ yield can be detected by a standard $b\bar{b}\tau\tau$ analysis, such as that discussed in the previous section The present study shows that the branching fraction for H^0, $A^0 \to \tau\tau$ can be determined to ± 0.15 and that for A^0, $H^0 \to b\bar{b}$ to ± 0.07, from which a limit $|A_\tau| < 250$ GeV can be derived. This constraint suppresses the tail at low values of Ω_χ bringing the prediction for the neutralino relic density to a relative accuracy of 0.08, which is comparable to the current accuracy from the WMAP data.

IV. CONCLUSIONS

We have studied the $e^+e^- \to H^0A^0$ process at $\sqrt{s}$ = 1 TeV using on fully simulated and reconstructed events for a Supersymmetric benchmark point where the mass of the A^0 boson is 419 GeV and the relic Dark Matter density in the Universe crucially depends on its mass and width. We find that the analysis of 2 ab^{-1} of data should probide with relative accuracies of 1.0 GeV and 2.9 GeV in the heavy boson masses and widths, respectively. The branching fractions of the $\tau^+\tau^-$ decay can be determined with a 0.15 relative accuracy. These data, in combination with other measurements available at the LHC and a e^+e^- linear collider, allows to infer the neutralino relic density in the Universe with a relative accuracy of 0.08.

Acknowledgments

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